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Spin Correlation in $t\bar{t}$ Production from $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

The DØ collaboration has performed a study of spin correlation in $t\bar{t}$ production for the process $t\bar{t} \rightarrow bW^+\bar{b}W^-$, where the W bosons decay to $e\nu$ or $\mu\nu$. A sample of six events was collected during an exposure of the DØ detector to an integrated luminosity of approximately 125 pb^{-1} of $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions. The standard model (SM) predicts that the short lifetime of the top quark ensures the transmission of any spin information at production to the $t\bar{t}$ decay products. The degree of spin correlation is characterized by a correlation coefficient κ. We find that $\kappa > -0.25$ at the 68% confidence level, in agreement with the SM prediction of $\kappa = 0.88$.

Pair production of top quarks has been observed [1] in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV by both the CDF and DØ collaborations, and the mass and production cross section have been measured in various channels [2,3]. The observed properties agree well with predictions from the standard model (SM).

For a top quark mass of $m_t = 175$ GeV, the width of the top quark in the SM is $\Gamma_t = 1.4$ GeV [4] while the typical hadronization scale is $\Lambda_{\rm QCD} \approx 0.22$ GeV [5]. The time scale needed for depolarization of the top-quark spin is of the order $m_t/\Lambda^2_{\rm QCD} \gg 1/\Gamma_t$ [6], implying that polarization information should be transmitted fully to the decay products of the top quark. That is, the expected lifetime of the top quark is sufficiently short to prevent long distance effects (e.g. fragmentation) from affecting the $t\bar{t}$ spin configurations, which are determined by the short distance dynamics of QCD at production [7–11].

The observation of spin correlation in the decay products of $t\bar{t}$ systems is interesting for several reasons. First, it provides a probe of a quark that is almost free of confinement effects. Second, since the lifetime of the top quark is proportional to the Kobayashi-Maskawa matrix element $|V_{tb}|^2$, an observation of spin correlation would yield information about the lower limit on $|V_{tb}|$, without assuming that there are three generations of quark families [12]. Finally, many scenarios beyond the standard model [13–16] predict different production and decay dynamics of the top quark, any of which could affect the observed spin correlation.

In the decay of a polarized top quark, charged leptons or quarks of weak isospin $-\frac{1}{2}$ are most sensitive to the initial polarization. Their angular distribution in the rest frame of the top quark is given by $1 + \cos\theta$, where θ is the angle between the polarization direction and the line of flight of the charged lepton or down-type quark. Due to the experimental difficulties of identifying jets initiated by a down-type quark, we only consider top-quark events in dilepton channels, i.e., where both W bosons in an event decay leptonically ($e\nu$ or $\mu\nu$). The advantages associated with using these channels are that: (1) objects sensitive to the polarization of the top quark are clearly identified, (2) background is small compared to the lepton+jets channels, and (3) there are fewer ambiguities associated with assigning objects observed in the detector to their originating quarks. The disadvantages are that the number of events in the dilepton channels is small, and that it is necessary to reconstruct two neutrinos in an event whose combined transverse momenta gives rise to the observed transverse momentum imbalance in the event.

At $\sqrt{s} = 1.8$ TeV, 90% of the top quark pairs arise from $q\bar{q}$ annihilation, and, for unpolarized incident particles, the produced t and $\bar{t}$ are also expected to be unpolarized. However, their spins are expected to have strong correlation [12,17] event by event and point along the same axis in the $t\bar{t}$ rest frame [18]. In an optimized spin quantization basis called the "off-diagonal" basis, contributions from opposite spin projections for top quark pairs arising from $q\bar{q}$ annihilations are suppressed at the tree-level [18] and only like spin configurations survive. This spin quantization basis can be specified using the velocity β^* and the scattering angle θ^* of the top quark with respect to the center-of-mass frame of the incoming partons. The direction of the off-diagonal basis forms an angle ψ with respect to the $p\bar{p}$ beam axis that is given by [18,20]:

$$\tan\psi = \frac{\beta^{*2}\sin\theta^*\cos\theta^*}{1 - \beta^{*2}\sin^2\theta^*}. \tag{1}$$

This particular choice of basis is optimal in the sense that top quarks produced from $q\bar{q}$ will

have their spins fully aligned along this basis. In the limit of top quark production at rest ($\beta^* = 0$), the t quark and the $\bar{t}$ quark will have their spins pointing in the same direction along $\psi = 0$.

Defining θ_+ as the angle between one of the charged leptons and the axis of quantization in the rest frame of its parent top quark, and similarly defining θ_- for the other charged lepton, the spin correlation can be expressed as [18,19]:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1 + \kappa\cos\theta_+ \cdot \cos\theta_-}{4}, \tag{2}$$

where the correlation coefficient κ describes the degree of correlation present prior to imposition of selection criteria or effects of detector resolutions. For $t\bar{t}$ production at the Tevatron, the SM predicts $\kappa = 0.88$ [21]. In the off-diagonal basis, the correlation coefficient for $q\bar{q} \to t\bar{t}$ is $\kappa = 1$. When $gg \to t\bar{t}$ is included at $\sqrt{s} = 1.8$ TeV, the correlation is reduced to $\kappa = 0.88$. The distribution is symmetric with respect to the exchange of θ_+ and θ_-, and it is therefore not necessary to identify the electric charge of the leptons. The physical meaning of κ in any spin quantization basis corresponds to the fractional difference between the number in which the top-quark spins are aligned and the number of events in which they have opposite directions.

The events used in this analysis are identical to those used to extract the mass of the top quark in our dilepton sample [2]. They were recorded using the DØ detector [22], which consists of a non-magnetic tracking system including a transition radiation detector (TRD), a liquid-argon/uranium calorimeter segmented in depth into several electromagnetic (EM) and hadronic layers, and an outer toroidal muon spectrometer. The final sample consists of three $e\mu$ events, two ee events, and one $\mu\mu$ event, with expected backgrounds of 0.21 ± 0.16, 0.47 ± 0.09, and 0.73 ± 0.25 events, respectively [2].

To study the distribution in $(\cos\theta_+, \cos\theta_-)$, we must deduce the momenta of the two neutrinos. The weighting scheme we use is the previously-developed neutrino weighting method [2]. In this method, each neutrino rapidity is selected from a range of values following a distribution consistent with the decay kinematics in $t\bar{t}$ events. We assume the $t\bar{t}$ dilepton decay hypothesis, and the constraints that $m(l_1\nu_1) = m(l_2\nu_2) = m_W$ and $m(l_1\nu_1 b_1) = m(l_2\nu_2 b_2) = m_t$. The problem can be solved by providing a specific input mass m_t that we assume to be $m_t = 175$ GeV. We then solve for the neutrino momentum vectors, obtaining up to four solutions, and assign a weight to each solution to characterize how likely it is to represent $t\bar{t}$ production. A weight is assigned to each solution based on the extent to which the sum of transverse momentum components $\sum p_k(\nu\nu)$ $(k = x, y)$ of the two neutrinos in the solution agrees with the measured missing transverse momentum component $\not{E}_k$ $(k = x, y)$ in the event. A Gaussian distribution with a width of 4 GeV is assumed for each component of the $\not{E}_k$ [2]. The weight is calculated as:

$$w^\nu = \prod_{k=x,y} \exp\left[-\frac{(\not{E}_k - p_k(\nu\nu))^2}{2\sigma^2}\right]. \tag{3}$$

The physical objects in the events are smeared to take into consideration the finite resolution of the detector, and we consider both possible pairings of the two charged leptons with the two jets assigned to b quarks. The presence of a third jet is also taken into consideration [2].

TABLE I. Asymmetry values for the 6 dilepton events at DØ .

Event Number	Event type	$\mathcal{A}$
10822	ee	0.34
12814	$e\mu$	-0.16
15530	$\mu\mu$	0.50
26920	$e\mu$	0.85
30317	ee	0.52
417	$e\mu$	-0.19
$< \mathcal{A} >$		0.31 ± 0.22

For each solution, we can then boost the decay products into the rest frame of the original top quarks and calculate the relevant decay angles $(\cos\theta_+, \cos\theta_-)$. The event fitter returns many such solutions for an event, and the goal is to deduce the original value of $(\cos\theta_+, \cos\theta_-)$ from the reconstructed distributions.

The differential cross section depends on the product $\xi = \cos\theta_+ \cdot \cos\theta_-$. We define an asymmetry $\mathcal{A}$ for all solutions in an event as [7,10,18]:

$$\mathcal{A} = \frac{1}{\sigma}\left(\int_0^1 \frac{d\sigma}{d\xi} d\xi - \int_{-1}^0 \frac{d\sigma}{d\xi} d\xi\right). \tag{4}$$

For perfect resolution and acceptance, $\mathcal{A}$ is expected to be $\kappa/4$.

Since the event fitter returns solutions with assigned weights and there is no "unique" solution, we sum the weights for all the solutions to populate the distribution ξ, which is shown in Fig. 1 for the 6 events. The values of $\mathcal{A}$ are listed in Table I.

Monte Carlo event generators such as HERWIG [23] and PYTHIA [24], in their current implementation, do not take proper account of spin correlation in $t\bar{t}$ production, and the two top quarks in an event are made to decay independently of each other, i.e. $\kappa = 0$ is assumed. To include the effects of spin correlation, $t\bar{t}$ events from the PYTHIA event generator are sampled at the generator level with the weight $(1 + \kappa\xi)$, where ξ is calculated from information at the generator level. We have checked this method against a Monte Carlo containing a fully correlated matrix element (where $\kappa = 1$ for $t\bar{t}$ events initiated from $q\bar{q}$ annihilation) and found the two methods are equivalent [21].

To estimate the sensitivity of our method, we created 1500 ensembles of 6 events consisting of appropriate fractions of $t\bar{t}$ signal and background. From Monte Carlo studies, we expect $\mathcal{A} = 0.207 \pm 0.006$ for full spin correlation ($\kappa = 1$) when all detector and background effects are included, while $\mathcal{A} = 0.25$ for perfectly reconstructed events without any background. The statistical uncertainty on our measurements is estimated to be 0.20 from these ensemble studies. Similar tests were performed for ensembles of 6 events without spin correlation ($\kappa = 0$), and we find an expected $\mathcal{A} = 0.115 \pm 0.005$, while ideally $\mathcal{A} = 0$. The main cause for loss of sensitivity is the incorrect pairing of the lepton with the jet. This produces a strong bias in $\mathcal{A}$ [21]. From the Monte Carlo samples generated with values of κ between -1 and 1, we find a linear relationship between $\mathcal{A}$ and κ: $\mathcal{A} = 0.112 + 0.088\kappa$.

We obtain $\mathcal{A} = 0.31 \pm 0.22$ from our data, which translates into $\kappa = 2.3 \pm 2.5$, assuming that a linear relationship between $\mathcal{A}$ and κ also holds beyond $-1 \leq \kappa \leq 1$, though the values $|\kappa| > 1$ are not physical.

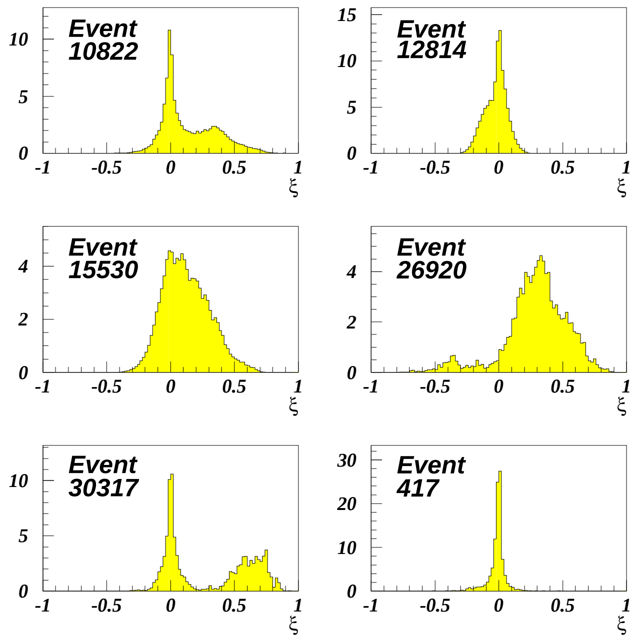

FIG. 1. Distribution of ξ for the 6 dilepton events.

Systematic uncertainties are negligible compared to the statistical uncertainty in our result. Varying the top quark mass by 5 GeV results in a shift in $\mathcal{A}$ of 0.01. There has been no theoretical calculation of effects of gluon radiation on the spin correlation of the top quarks. However, these effects were studied for spin-uncorrelated events (i.e. $\kappa = 0$) by including gluon radiation in the PYTHIA event generator. This results in a shift in $\mathcal{A}$ of 0.0065 ± 0.0063, where the error is due to finite Monte Carlo statistics. The asymmetry distribution expected from background is similar to that for spin-uncorrelated $t\bar{t}$ events, and its impact is small.

To maximize the physical information present in the data, the full two-dimensional phase space of $(\cos\theta_+, \cos\theta_-)$ is used in a two-dimensional binned likelihood analysis. The phase space is split into a 3×3 grid, each side of which spans 1/3 of the range of $\cos\theta_+$ and $\cos\theta_-$. The nine bins are populated for data with weights $(w_1, ..., w_9)$ from the event fitter, with the distribution of weights for each event normalized to unity. Similar distributions are made for the generated Monte Carlo events using different values of κ for $t\bar{t}$ signal and an appropriate admixture of background. Comparisons of data with Monte Carlo are used to extract κ.

Because an event populates each bin with fractional probability, a simple likelihood assuming a Poisson distribution may not be appropriate. Moreover, since the weights for each event satisfy the normalization condition $\sum_i w_i = 1$, only eight out of the nine weights are independent, and there are correlations among the weights in any given event.

To find eight independent variables, the covariance matrix $C_{ij} = \mathrm{cov}(w_i, w_j), (i, j =$

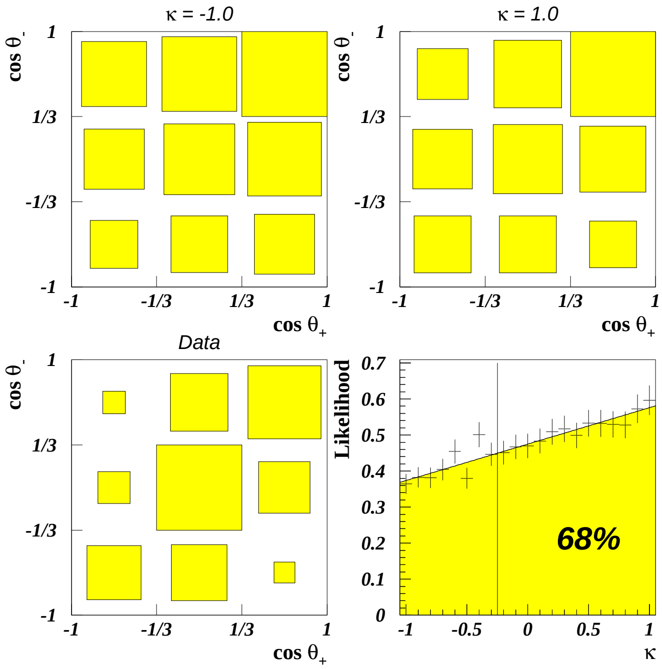

FIG. 2. Plots of probability density for $t\bar{t}$ events in the dilepton channels in $(\cos\theta_+, \cos\theta_-)$ phase space. Top left: Monte Carlo events with $\kappa = -1$; top right: Monte Carlo events with $\kappa = +1$; bottom left: our data; and bottom right: the likelihood as a function of κ showing the 68% confidence limit of $\kappa > -0.25$. The box area is proportional to the summed weights in the bin.

$1, \ldots, 8)$ is calculated from the Monte Carlo events for a given spin correlation κ and background, and diagonalized using a matrix A, such that $A^{-1}CA$ has only diagonal elements. The new independent variables (i.e. diagonalized weights) are found by applying this transformation matrix to the weights, $V = A^{-1}W$, where $W = (w_1, \ldots, w_8)^T$ and $V = (v_1, \ldots, v_8)^T$. The distributions f_i $(i = 1, \ldots, 8)$ of the new variables v_i are used to define the likelihood

$$\mathcal{L}(\kappa) = \prod_{i}^{N} \prod_{j=1}^{8} f_j(v_{ij}; \kappa), \tag{5}$$

where v_{ij} are the new variables for ith event and N is the number of events. By explicitly constructing the likelihood, we do not have to make any assumptions about the underlying distributions of the weights.

The result is shown in Fig. 2. The probability densities for the Monte Carlo generator at $\kappa = -1$ and $\kappa = 1$ are shown for comparison. From the dependence of the likelihood on κ, we can set a 68% confidence interval at $\kappa > -0.25$, based on the line fit, in agreement with the SM prediction of $\kappa = 0.88$.

In conclusion, we have presented a search for spin correlation effects in the production of $t\bar{t}$ pairs in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, where the dominant production mechanism is

expected to be the annihilation of incident $q\bar{q}$ states. This analysis makes use of the fact that there exists an optimal spin quantization basis for the produced top quarks, and that the charged leptons from top-quark decays are most sensitive to the polarization of the top quark. From this analysis, we conclude that $\kappa > -0.25$ at the 68% confidence level, which is compatible with correlation of spins expected on the basis of the standard model.

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REFERENCES

[1] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **74**, 2626 (1995); DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **74**, 2632 (1995).

[2] DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **79**, 1197 (1997); DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **79**, 1203 (1997); DØ Collaboration, B. Abbott *et al.*, Phys. Rev. D **58**, 052001 (1998); DØ Collaboration, B. Abbott *et al.*, Phys. Rev. Lett. **80**, 2063 (1998); DØ Collaboration, B. Abbott *et al.*, Phys. Rev. D **60**, 012001 (1999); DØ Collaboration, B. Abbott *et al.*, Phys. Rev. D **60**, 052001 (1999); DØ Collaboration, B. Abbott *et al.*, Phys. Rev. Lett. **83**, 1908 (1999).

[3] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 1992 (1997); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 3585 (1997); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **80**, 2767 (1998); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **80**, 2773 (1998); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **80**, 2779 (1998); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **82**, 271 (1999); CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **59**, 092001 (1999).

[4] M. Jeżabek, Nucl. Phys. B (Proc. Suppl.) **37**, 197 (1994).

[5] Particle Data Group, C. Caso *et al.*, Eur. Phys. J. **C 3**, 1 (1998).

[6] A.F. Falk and M.E. Peskin, Phys. Rev. D **49**, 3320 (1994).

[7] I. Bigi, Phys. Lett. B **175**, 233 (1986).

[8] I. Bigi, Y. Dokshitzer, V. Khoze, J. Kühn, and P. Zerwas, Phys. Lett. B **181**, 157 (1986).

[9] M. Jeżabek and J. Kühn, Phys. Lett. B **329**, 317 (1994).

[10] R.H. Dalitz and G.R. Goldstein, Phys. Rev. D **45**, 1531 (1992).

[11] R.H. Dalitz and G.R. Goldstein, Int. Jour. Mod. Phys. **A9**, 635 (1994).

[12] T. Stelzer and S. Willenbrock, Phys. Lett. B **374**, 169 (1996).

[13] C. Hill and S. Parke, Phys. Rev. D **49**, 4454 (1994).

[14] E. Eichten and K. Lane, Phys. Lett. B **327**, 129 (1994).

[15] B. Holdom and T. Torma Phys. Rev. D **60**, 114010 (1999).

[16] Kang Young Lee *et al.*, Phys. Rev. D **60**, 093002 (1999).

[17] V. Barger, J. Ohnemus, and R.J.N. Phillips, Int. J. Mod. Phys. **A4**, 617 (1989).

[18] G. Mahlon and S. Parke, Phys. Rev. D **53**, 4886 (1996); G. Mahlon and S. Parke, Phys. Lett. B **411**, 173 (1997).

[19] G.R. Goldstein, in *Spin 96: Proceedings of the 12th International Symposium on High Energy Spin Physics, Amsterdam, 1996*, edited by C.W. deJager (World Scientific, 1997), p. 328.

[20] S. Parke and Y. Shadmi, Phys. Lett. B **387**, 199 (1996).

[21] S. Choi, Ph.D. dissertation, Seoul National University, 1999 (unpublished) http://www-d0.fnal.gov/results/publications_talks/thesis/choi/thesis.ps.

[22] DØ Collaboration, S. Abachi *et al.*, Nucl. Instrum. Methods in Phys. Res. A **338**, 185 (1994).

[23] G. Marchesini *et al.*, Comput. Phys. Commun. **67**, 465 (1992).

[24] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).